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Investigation of the effect of water content and degree of compaction on the shear strength of clay soil material

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The effect of water on compacted clay material with the use of triaxial compression was studied, and models for predicting shear strength parameters were also developed. The results show that cohesion decreases exponentially with increasing water content and exponentially increases with increasing degree of compaction. The angle of internal friction decreases in a convex quadratic parabolic law with increasing water content and increases with a concave quadratic parabolic law with an increase in the degree of compaction; Cohesion and internal friction angle are two-dimensional quadratic functions of water content and degree of compaction and have relatively large values of the shear strength parameter.
Keywords: compacted clayey soil material, shear strength, water content, degree of compaction, cohesion, internal friction angle.

Разработаны модели прогнозирования параметров прочности материала на сдвиг. Исследовано влияние воды на прочность уплотненого глинистого материала с использованием трехосевой компрессии. Результаты показывают, что когезия экспоненциально уменьшается с увеличением содержания воды и экспоненциально возрастает с увеличением степени уплотнения. Угол внутреннего трения уменьшается по выпуклому квадратичному параболическому закону с увеличением содержания воды и возрастает по вогнутому квадратичныму параболическому закону с увеличением степени уплотнения. Когезия и внутренний угол трения являются двумерными квадратичными функциями содержания воды и степени уплотнения и имеют относительно большие значения параметра прочности на сдвиг.

Дослідження впливу вмісту води і ступеня ущільнення на міцність зсуву матеріалу глинистого грунту. *Чжан Хучжу, Лю Ханбінг, Ван Цзин, Дун Вейчжі*

Розроблено моделі прогнозування параметрів міцності матеріалу на зрушення. Досліджено вплив води на міцність ущільнення глинистого матеріалу з використанням трехосевой компресії. Результати показують, що когезия експоненціально зменшується зі збільшенням вмісту води і експоненціально зростає зі збільшенням ступеня ущільнення. Кут внутрішнього тертя зменшується по опуклому квадратичному параболічного закону зі збільшенням вмісту води і зростає по увігнутому квадратічниму параболічного закону зі збільшенням ступеня ущільнення. Когезия і внутрішній кут тертя є двовимірними квадратичними функціями вмісту води і ступеня ущільнення і мають відносно великі значення параметра міцності на зрушення .

1. Introduction

As the foundation of pavement structure, a solid and stable subgrade can provide an important guarantee for pavement structure's long-term bearing of vehicle load. Some common problems of subgrade and pavement, such as subgrade subsidence, subgrade slope collapse and ruts are often caused by the insufficient bearing capacity of subgrade. As the representation of the resistance capacity of soil mass to shear failure, shear strength is a key parameter for the stability analysis of subgrade side slope, assessment of subgrade bearing capacity and the calculation of earth pressure of bracing structures. Therefore, it is of great theoretical significance and practical engineering value to assess the shear strength properties of subgrade compacted soil correctly and reliably for guiding the design and construction of subgrade and guaranteeing the strength and stability of subgrade and pavement structure.

The factors which affect the shear strength properties of subgrade compacted clayey soil material include soil type, water content, degree of compaction, state of stress and so on. For the specific subgrade compacted soil, the water content and degree of compaction are definitely the most important factors for its shear strength properties. As for the influence of water content and degree of compaction on the shear strength properties of compacted soil, there have been many beneficial researches carried out at home and abroad at present. Through the study on compacted clayey soil material, Cokca et al.[1] concluded that suction and internal friction angle decreased with the increase of compaction water content, the cohesion peak appears around the optimum water content and other conclusions by the direct shear test and suction measurement of compacted clayey soil material; through the direct shear test of the shear strength properties of remodeled unsaturated soil, Shen et al.[2] concluded that the cohesion and internal friction angle of unsaturated soil decreased linearly with the increase of water content and the decrease of cohesion was more apparent. The dry density had little impact on the internal friction angle of unsaturated soil, while the cohesion increased exponentially with dry density; through the indoor direct shear test of the clayey soil from Luojia Hills; Hu et al.[3] found that the cohesion varies in "inverse S shape" and the internal friction angle decreased generally with the increase of compaction water content; through the statistics of the direct shear test of the compaction loess-like silty soil in a place in Lvliang City of Shanxi Province, Wang et al.[4] got the linear-trend equation of shear strength parameters with the variation of water content and dry density and found that the cohesion and internal friction angle increase and decrease respectively with the increase in dry density and the increase in water content; through the direct shear test of the red soil in Nanchang area, Liu et al.[5] found that the influence of water content and dry density on shear strength parameters are not simply linear relationship: under the same dry density condition, the shear strength decreases with the increase of water content, and under the same water content condition, the cohesion increases with the increase of dry density, while the relationship between internal friction angle and dry density is relatively complex; through the direct shear test of the rock soil in the dumping site of Yimin Open Pit of Yimin coalfield in Inner Mongolia Autonomous Region, Wang et al.[6] found that with the same degree of compaction, cohesion decreases slowly first and sharply later and the internal friction angle decreases slightly with the increase of the mass fraction of water content. With the same mass fraction of water content, cohesion increases slowly first and sharply later and the internal friction angle increases slightly with the increase in the degree of compaction; by analyzing the result of direct shear test, Yuan et al.[7] found that the cohesion and internal friction angle of subgrade compacted soil increase with the increase of the degree of compaction and the cohesion peak appears around the optimum water content, and when water content was higher than the optimum water content, cohesion decreases sharply and the internal friction angle decreases with the increase of water content.

The above research results show that there is no consensus for the influence of water content and degree of compaction on the shear strength properties at present and there are still very few studies on the specific functional relationship between shear strength parameters and the water content as well as the degree of compaction and on the prediction model. For that, this paper takes the widely used clayey soil material in the highway engineering as research object. Taking the requirement for the degree of compaction of the highway subgrade and the water content condition during the use term into consideration, test studies on the shear strength properties of subgrade compacted clayey soil material under different degree of compaction and water content are carried out and the functional relationship between shear strength parameters and the water content as well as the degree of compaction are analyzed, and the prediction model of shear strength parameters which comprehensively considers the water content and degree of compaction is established, so as to provide theoretical basis and reference for the design and construction practice of highway subgrade.

Table 1. Basic physical properties of test soil

Natural Water Content /%	Liquid Limit Water Content /%	Plastic Limit Water Content /%	Plasticity Index /%
26.7	35.9	20.6	15.3

Specific Gravity of Soil Particle	Optimum Water Content /%	Maximum Dry Density /(g·cm^{-3})
2.65	15.3	1.86

2. Test Soil and Test Scheme

2.1 Test Soil

The soil used in the test was from the borrow pit of the CP05 contract section of Siping-Changchun Reconstruction Project of Beijing-Harbin Expressway project. According to the relevant requirements in the Test Methods of Soils for Highway Engineering (JTG E40-2007), the soil samples was named as clayey soil material based on the test results of particle analysis, joint tests of liquid-plastic limit and organic matter content test. The basic physical property of this clayey soil material is shown in Table 1 and the particle size distribution curve is shown in Fig. (1).

2.2 Test Specimen Preparation

The testing soil was grinded by wooden roller on a rubber plate and then screened by 2mm sieve after being naturally dried in lab. The required mass of air-dried soil and water added volume were calculated on the basis of the optimum water content, degree of compaction, number of specimens and the water content of the air-dried soil specified by the test requirement. Then the soil samples were put into non-bibulous mixing containers and were sprayed the estimated water. After mixed evenly and wetted under seal for one day and night, the soil samples were compacted into ∅39.1mm×80mm cylindrical test specimens with static compacting method. The geometric dimensioning and mass of specimens were measured by vernier caliper and electronic balance respectively after demolding and the density was calculated then. The value difference between the density and preparation standard of specimens of the same group was below 2%. And then specimens that meet the requirement were put into sample trays to air-dry or humidify to the prearranged water content indoor or in the constant humidity cabinet. After that specimens were covered tightly with plastic film after the data were reordered. Specimens can use for the shear strength property test until the inner water content is well-distributed.

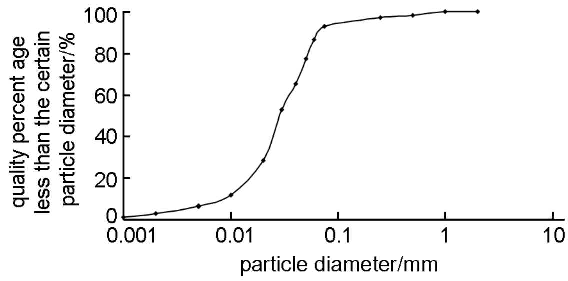

Fig. 1. Curve of soil particle gradation.

2.3 Test Device

The test loading device was the TSZ-1B automatic triaxial apparatus developed by Nanjing Zhilong Technology Co., Ltd., which is the dedicated device for testing mechanical parameters of soil, with the functions of uniaxial compression and triaxial compression, a maximum axial load of 10kN and a maximum confining pressure of 2 MPa. Manual or computer automation control can be chosen during the testing process and the shear rate is adjustable in the range of 0~4.8mm/min. The testing data were automatically collected and processed by computer program. The mechanical parameters such as the relationship curve of principal stress difference and axial strain, peak of shear, cohesion and internal friction angle under different test conditions could be obtained.

2.4 Test Scheme and Test Method

Previous studies[8] have shown that the water content of subgrade generally varies from 8%~20%. According to the requirements of Code for Design of Highway Subgrades (JTG D30-2015), the degree of compaction of subgrade soil generally varies from 90%~100% based on different highway grades and different subgrade parts. To make a comprehensive research into the shear strength properties of subgrade compacted soil under different conditions of water content and degree of compaction and simulate the actual work conditions of subgrade, the test was carried out at five levels of water content (9.3%, 12.3%, 15.3%, 18.3% and 21.3%) and five levels of degree of compaction (85%, 90%, 93%, 96% and 99%), so there were 25 test groups in total. The unconsolidated and undrained method was adopted in the triaxial compression test of soil. Three values of confining pressure, namely, 100kPa, 200 kPa and 300kPa were adopted. The peak value of principal stress difference or the principal stress difference value at 15% axial strain when there was no peak value was taken as the fail point.

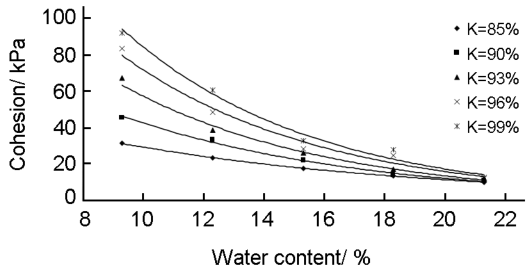

Fig. 2. Relationships between cohesion and water content.

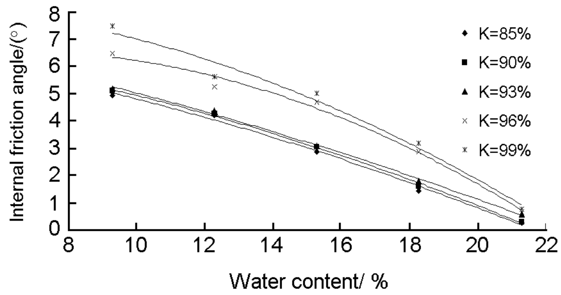

Fig. 3. Relationships between internal friction angle and water content.

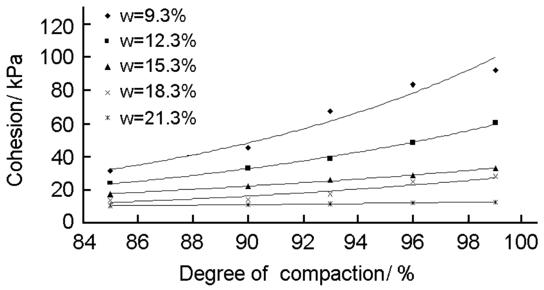

Fig. 4. Relationships between cohesion and degree of compaction.

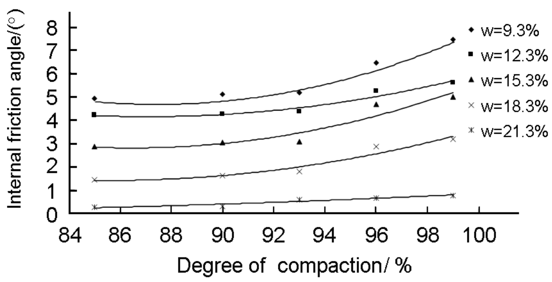

Fig. 5. Relationships between internal friction angle and degree of compaction.

3. Test Results and Discussion

According to Mohr-coulomb Strength Theory, shear strength parameters of subgrade compacted soil contain cohesion c and internal friction angle ϕ. By collecting and analyzing the result of the test, the curve of changes of cohesion and internal friction angle with water content w and degree of compaction K was obtained (see Fig. (2-5)). To represent the changing trend of cohesion and internal friction angle with water content and degree of compaction more intuitively and clearly, nonlinear regression analysis was conducted for test data, and the fitting equation at different water content and degree of compaction (see Table 2-3) is obtained.

3.1 Effect of water content on shear strength parameters

3.1.1 Effect of water content on cohesion

The change curve of the cohesion of subgrade compacted clayey soil material following the change of water content is as Fig. (2), which indicates that the changing trends of cohesion of subgrade compacted clayey soil material with water content under different degrees of compaction are basically consistent, decreasing with the increase of water content. Among that, when water content is lower than optimum water content, the change is greater while the change becomes slight when water content is higher than optimum water content.

According to the interaction mechanism between mineral particles and water in subgrade compacted clayey soil material, the liquid water in soil can be divided into absorbed water, capillary water and gravitational water based on the different influence of double electrode layer in the surface of soil particles, and the cohesion of soil is generated by the coupling effect of absorbed water, cementation of some materials as well as coupling effect of capillary water and ice [9]. When the water content of subgrade compacted clayey soil material is relatively low, the absorbed water film surrounding soil particles is relatively thin, and the coupling effect of absorbed water is relatively strong, and accordingly cohesion is relatively strong. With the increase of water content, the absorbed water film will thicken, and hydrogel bond through public absorbed water film will gradually weaken, so cohesion reduces consequently. Besides, the difference of the coupling effect between absorbed water and free water will become weaker with the increase of its distance to the surface of soil particles, which is indicated by the gradual decrease of the change range of cohesion with the increase of water content. From the theories mentioned above, we can predict that, when water content increases to a certain degree, the coupling effect of absorbed water will disappear for the water film is too thick, and the cementation of some materials will disappear due to the dissolution of cement, and the coupling effect of capillary water will be destroyed because of soaking, and the cohesion of subgrade compacted soil will be very small or even disappear. The predicted conclusion and the change trend of the test curve in Fig. (**2**) are consistent.

Table 2. Fitting equations of the variation of cohesion and internal friction angle with water content

Degree of Compaction /%	Cohesion/kPa	
	Fitting Equation	Correlation Coefficient
85	$c = 75.41e^{-0.095w}$	0.999
90	$c = 149.46e^{-0.126w}$	0.998
93	$c = 243.76e^{-0.145w}$	0.998
96	$c = 325.38e^{-0.151w}$	0.985
99	$c = 413.15e^{-0.159w}$	0.985

Degree of Compaction /%	Internal Friction Angle/(°)	
	Fitting Equation	Correlation Coefficient
85	$\phi = -0.008w^2 - 0.156w + 7.166$	0.997
90	$\phi = -0.009w^2 - 0.132w + 7.149$	0.999
93	$\phi = -0.006w^2 - 0.218w + 7.775$	0.999
96	$\phi = -0.026w^2 - 0.314w + 5.624$	0.995
99	$\phi = -0.018w^2 - 0.039w + 8.461$	0.991

3.1.2 Effect of water content on internal friction angle

Fig. (3) is the curve of the change of internal friction angle of subgrade compacted clayey soil material with water content, which indicates that the internal friction angles at different degrees of compaction will decrease with the increase of water content, and the change trends are basically consistent. The interaction mechanism between soil particles and water can also be used to explain the phenomenon mentioned above. When water content is low, the absorbed water film on the surface of soil particles is rather thin, and the action between soil particles is mainly attractive force, and lubrication action of water film is insufficient, and the resistance of relative displacement between particles is relatively large. As a result, it is accordingly indicated that there is a larger internal friction angle of subgrade compacted clayey soil material. With the increase of water content and the increase in the thickness of absorbed water film, repulsion force between soil particles will gradually increase while attractive force will relatively decrease, together with the sufficient lubrication action of water film, the resistance of relative displacement between soil particles will decrease and internal friction angle will accordingly decrease.

3.1.3 Relationship between shear strength parameters and water content

The regression analysis of cohesion, internal friction angle and water content of subgrade compacted clayey soil material is indicated in Table **2**, in which the fitting result shows that at different degrees of compaction, with the increase of water content, cohesion will decrease exponentially, while internal friction angle will change in convex quadratic parabola rule. The correlation coefficients of fitting equation are all above 0.98, which reflects the relations between water content and shear strength parameter well.

3.2. Effect of degrees of compaction on shear strength parameters

3.2.1. Effect of degree of compaction on cohesion

The change curve of the cohesion of subgrade compacted clayey soil material with the degrees of compaction is indicated in Fig. (**4**) , from which we can see that with the same water content, cohesion will increase with the increase of degrees of compaction, and it will increase remarkably when the water content is low, while increase slowly when water content is high. In the direct shear test conducted by Wang et al. [10] for the research into the compacted loess in a construction field in Xi'an, similar conclusion was achieved. The interaction mechanism between soil particles and water can also be used to explain the effects of degrees of compaction on cohesion. The increase of degrees of compaction will make the subgrade compacted particles become more compact with less distance between soil particles. At this time, the hydrogel bond through public absorbed water film will increase gradually, and cohesion will accordingly increase. When water content is high and the water film is thick, and even free water exists, the strengthening hydrogel bond caused by the decrease of distance between soil particles will be weaker. As a result, the effect of degrees of compaction on cohesion is not that significant.

3.2.2 Effect of degree of compaction on internal friction angle

Fig. 5 shows the change curve of internal friction angle following the degrees of compaction of subgrade compacted clayey soil material, which indicates that the internal friction will increase with the increase of degrees of compaction. The reason is that the increase of degrees of compaction will make the soil particles become more compact and decrease the distance between soil particles, resulting in

Table 3. Fitting equations of the variation of cohesion and internal friction angle with degree of compaction

Water Content /%	Cohesion/kPa	
	Fitting Equation	Correlation Coefficient
9.3	$c = 0.032e^{0.081K}$	0.985
12.3	$c = 0.080e^{0.067K}$	0.998
15.3	$c = 0.387e^{0.045K}$	0.998
18.3	$c = 0.087e^{0.058K}$	0.944
21.3	$c = 2.461e^{0.016K}$	0.987

Water Content /%	Internal Friction Angle/(°)	
	Fitting Equation	Correlation Coefficient
9.3	$\phi = 0.020K^2 - 3.384K + 157.1$	0.987
12.3	$\phi = 0.011K^2 - 1.884K + 86.186$	0.970
15.3	$\phi = 0.015K^2 - 2.617K + 115.9$	0.945
18.3	$\phi = 0.011K^2 - 1.788K + 77.867$	0.966
21.3	$\phi = 0.001K^2 - 0.123K + 4.306$	0.958

the increase of mutual attraction and the resistance of relative displacement, and the internal friction angle increases accordingly.

3.2.3 Relationship between shear strength parameters and degree of compaction.

Table 3 shows the regression analysis results between the shear strength parameters and water content of subgrade clayey soil material. It can be seen from this table that there is the same functional relationship between cohesion and internal friction angle as well as the degree of compaction at different levels of water content respectively, of which the cohesion increases with the growth of degree of compaction in an exponential function law, while the internal friction angle changes with the growth of the degree of compaction in a concave quadratic parabola. The maximum value of correlation coefficient of fitting equation is 0.998, and its minimum value is 0.944, with a good correlation, thus better manifesting the relationship between the degree of compaction and the shear strength parameters.

4. Prediction Models of shear strength parameters

It can been seen from the analysis of the above mentioned test results that, there is excellent nonlinear correlation between the shear strength parameters, cohesion and internal friction angle of subgrade compacted clayey soil material and their water content and degree of compaction. For that, polynary nonlinear regression analyses is made on the shear strength parameter values at different levels of water content and degree of compaction to form the quantitative function relationship $c(\text{or } \phi) = f(w, K)$. Preliminary analysis shows that the binary quadratic function relations are better satisfied between cohesion and the internal friction angle and the water content and the degree of compaction. The tentative regression formula is as follows:

$$c(or\phi) = p_1 w^2 + p_2 K^2 + p_3 wK \quad (1)$$

Where,

p_1, p_2 and p_3 —the non-dimensional parameters;

w —the water content of subgrade compacted soil material;

K — the degree of compaction of subgrade compacted soil material.

The test parameters p_1, p_2 and p_3 are fixed through iterative computation by using Levenberg-Marquardt and universal global optimization method. The results are shown in Table 4. In order to test the precision and applicability of the prediction model, five groups of tests at different levels of water content and degree of compaction are added. The comparison between predicated results and testing results is shown in Table 5. It can be seen from Table 4 and Table 5 that the correlation coefficients are respectively 0.961 and 0.979 and the predicted average errors are respectively 4.36 and 5.49, which indicates the prediction model has an ideal fitting result and high fitting precision and can accurately reflect the non-linear relationship between the cohesion and internal friction angle of the subgrade compacted clayey soil material and its water content and the degree of compaction, which can provide theoretical foundation and reference for the shear strength parameter value of the practical engineering with insufficient data.

The fitting surface of the shear strength parameters and the water content as well as the degree of compaction of the subgrade compacted clayey soil material is shown in Fig. (6-7). From Formula 1 and Fig. (6-7), it can be seen that the shear strength parameters, the internal friction angle and cohesion of the subgrade compacted clayey soil material develop in the law of binary

Table 4. Computing results of test parameters

Shear Strength Parameters	p_1	p_2	p_3	Correlation Coefficient
c	0.38882	0.02139	-0.17604	0.961
ϕ	-0.00799	0.00097	-0.00209	0.979

Table 5. Validation of Prediction Models

Water Content /%	Degree of Compaction /%	Cohesion/kPa		
		Prediction Value /kPa	Test Value /kPa	Prediction Deviation/%
9.3	85	49.00	44.56	9.95
12.3	90	37.19	38.07	2.32
15.3	93	25.51	25.75	0.93
18.3	96	18.05	18.55	2.69
21.3	99	14.80	13.98	5.90

Water Content /%	Degree of Compaction /%	Internal Friction Angle		
		Prediction Value /kPa	Test Value /kPa	Prediction Deviation/%
9.3	85	4.68	4.63	1.03
12.3	90	4.35	4.29	1.38
15.3	93	3.56	3.22	10.62
18.3	96	2.61	2.71	3.67
21.3	99	1.49	1.36	9.93

quadratic function, with the change of water content as well as the degree of compaction, decreasing with the increase of water content and rise with the increase of the degree of compaction. When the degree of compaction becomes larger, the cohesion and internal friction angle can increase significantly with the decline of water content; when the water content is small, the cohesion and internal friction angle can increase significantly with the increase of the degree of compaction. In addition, the compacted clay soil with higher degree of compaction and lower water content will have a higher shear strength parameter value. It is clear that well-completed subgrade surface drainage and underground drainage to reduce subgrade water content and properly improve the construction compaction standard can remarkably promote the shear strength of clayey soil material so as to guarantee enough bearing capacity and stability of subgrade structure.

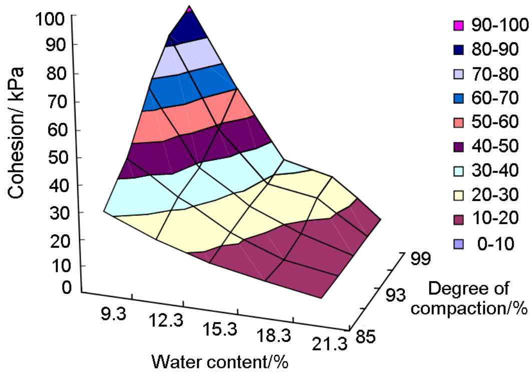

Fig. 6. Relationship surface between cohesion and water content and degree of compaction.

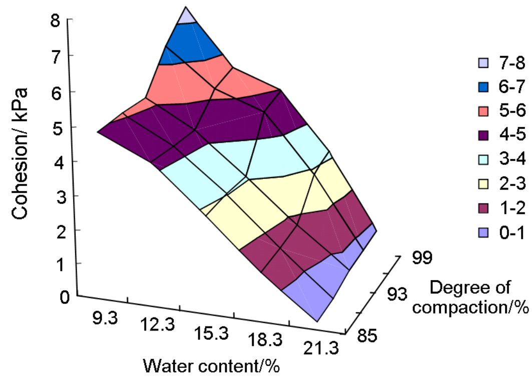

Fig. 7. Relationship surface between internal friction angle and water content and degree of compaction.

5. Conclusions

1) As for subgrade compacted clayey soil material, the shear strength parameter is markedly affected by water content and the degree of compaction. Within ranges of water content and compaction requirement of subgrade, both cohesion and the internal friction angle decrease with the increase of water content and gradually increase with the growth of the degree of compaction.

2) The shear strength parameter, the water content and the degree of compaction of subgrade compacted clayey soil material have a good nonlinear correlation, among which the cohesion and water content, the degree of compaction all follow the law of exponential function; the internal friction angle has a convex quadratic parabola function relationship with the water content, and a concave quadratic parabola function relationship with the degree of compaction.

3) Both the cohesion and the internal friction angle of subgrade compacted clayey soil material exhibit binary quadratic function relationships on water content and the degree of compaction, and the prediction model set up by

fitting presents a good correlation, which can provide the theoretical foundation and reference for the shear strength parameter value of the practical engineering without sufficient data.

4) With a higher degree of compaction or lower water content, the subgrade compacted clayey soil material is remarkably affected by water content and the degree of compaction and has a higher shear strength parameter value. Well-completed subgrade drainage to reduce subgrade water content and properly improve the construction compaction standard can remarkably improve the shear strength of the subgrade compacted clayey soil material so as to guarantee enough bearing capacity and stability of subgrade.

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